Technical Report ARAEW-TR-05009

Composite Gun Tube Support

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March 2005

REPORT DOCUMENTATION PAGE

1. REPORT DATE *(DD-MM-YYYY)* March 2005	2. REPORT TYPE FINAL	3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE Composite Gun Tube Support	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Andrew G. Littlefield, Joshua B. Root, and Martin Leach	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army ARDEC Benet Laboratories, RDAR-WSB Watervliet, NY 12189-4000	8. PERFORMING ORGANIZATION REPORT NUMBER ARAEW-TR-05009
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army ARDEC Benet Laboratories, RDAR-WSB Watervliet, NY 12189-4000	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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15. SUBJECT TERMS
Advanced Composites, Applications-Land Transportation, Military

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT U	18. NUMBER OF PAGES 13	19a. NAME OF RESPONSIBLE PERSON Andrew Littlefield
a. REPORT U/U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPONE NUMBER *(Include area code)* 518-266-3972

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COMPOSITE GUN TUBE SUPPORT

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ABSTRACT

The Future Combat Systems Multi-Role Armament and Ammunition System (FCS-MRAAS) Swing Chamber Launcher uses a rotating swing chamber to achieve a high rate of fire while simplifying design and minimizing space claims. Since the chamber is detached from the tube, the tube is held only where it screws into the breech ring. This single support point is insufficient to keep tube deflections to an acceptable level. To overcome this problem, a tube support was designed that connects to the front of the breech ring and to the gun tube 1060 mm forward of the breech ring. This tube support is a thin composite shell, constructed from IM7 and M55J carbon fibers with an epoxy matrix, which changes from a rectangular cross section in the rear to an octagonal cross section in the front. Titanium fittings are bonded to the shell at both ends for attachment. Two composite tube supports were built, assembled, and test fired at Aberdeen Proving Grounds. One was instrumented with six tri-directional strain gauge rosettes and three single axis accelerometers. This paper will go over the design, fabrication, and testing of the tube support and compare test results to finite element models.

KEY WORDS: Advanced Composites, Applications-Land Transportation, Military

1. INTRODUCTION

The FCS-MRAAS (Figure 1 and Figure 2) is a next generation weapon system that provides both indirect and direct fire; achieving firing rates as high as 20 rounds per minute; while weighing less than 16300 kg (18 tons). Advanced composite structures, such as the composite tube support, are playing a
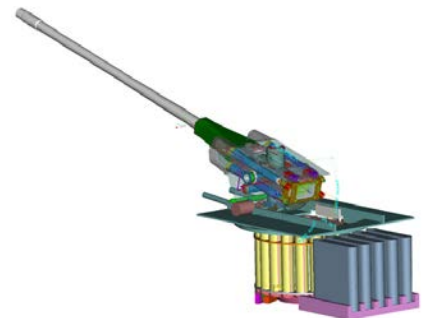
Figure 1. FCS-MRAAS Swing Chamber Launcher with autoloader
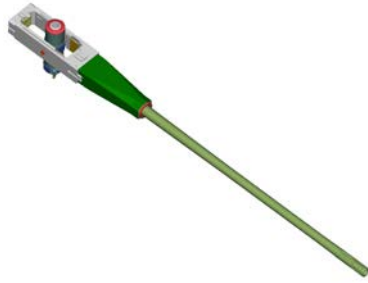
Figure 2. FCS-MRAAS Swing Chamber Launcher

major role in helping the Swing Chamber Launcher subsystem meet its weight goals. The swing chamber design was chosen for its overall benefits to the system. First, it enables the gun to be loaded while the tube is elevated and stabilized, as the chamber can rotate to its loading position independent of gun tube elevation.   Second, it enables a much simplified autoloader design. Both of these design innovations allow for higher rates of fire, but the major benefit is the significant weight and space claim reduction for the overall system.

Using a swing chamber helps to achieve these characteristics, but also presents some potential problems for the system. First, since the chamber is separate from the barrel, the connection between the chamber and the barrel must be sealed in addition to sealing the rear of the chamber as in a conventional system. Second, in a conventional gun tube design, the chamber would be part of the gun tube and the tube could be gripped in two places, providing an appropriate wheelbase to help with accuracy. With the swing chamber, however, the tube is screwed into the breech ring and is thus held only in one location. Supporting the tube at this one point is insufficient to keep tube deflections to an acceptable level.
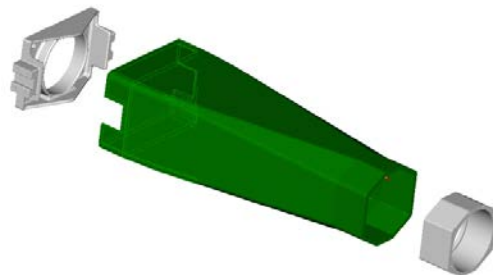
The composite tube support was designed to overcome the latter problem. Besides providing additional stiffness to the tube, the support also functions as the rear part of the tube's environmental shroud.
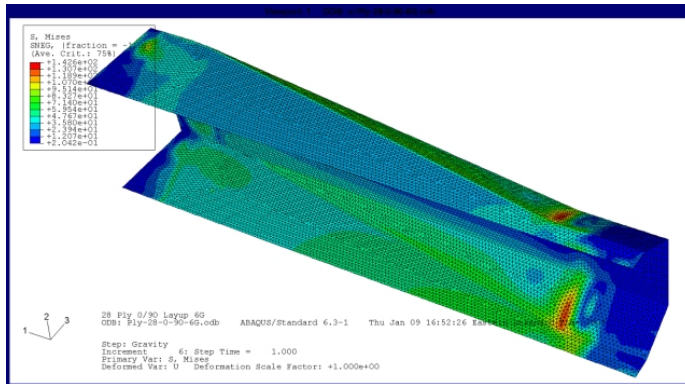
2. DESIGN

Even though the tube support had been envisioned as a composite part from the beginning, the initial baseline design was done as an all titanium piece. This baseline design, which used a 15 mm thick shell, was to set a design goal for the composite part. This goal was to have the muzzle deflections of the gun tube under a 6 g static load be equivalent for each part, while minimizing weight. A static load was used for quicker computation time. The drawback to this approach was that the overall shape of the tube support was determined by the titanium design.

The shape of the tube support is a thin shell which changes from the rectangular cross section of the breech ring in the rear to the circular cross section of the tube in the front, as seen in Figure 2 and Figure 3. This shape was caused by the shapes of the titanium end frames, which were designed at the same time as the baseline titanium shell. This shape complicated not only the design but also the manufacturing of the part. With its sharp corners, this shape was less than ideal for a composite part, but it still performed surprisingly well.

A finite element analysis (FEA) model was created in Abaqus for the all titanium design. It was a three-dimensional half model incorporating the tube support, gun tube, partial breech ring and associated hardware. The connection between the gun tube and the wedge ring at the front of the tube support was modeled as finite sliding, while all other connections

Figure3. Tube Support Exploded View

Figure 4. Stresses in the composite shell under a 6 g loading using smeared properties
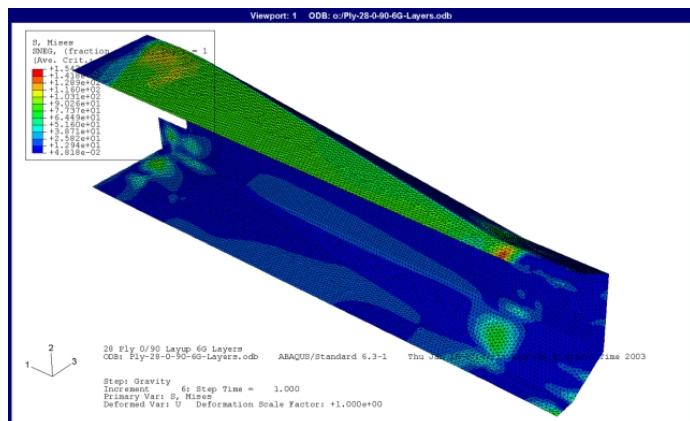
were made using tie constraints. The initial model consisted of linear solid elements with the shell and the rear end frame being tetrahedral elements (C3D4) while the rest of the model used brick elements (C3D8R). Under a 1 g static loading the vertical muzzle deflection was predicted to be 11 mm, whereas under a 6 g static load it was predicted to be 64 mm.

Once the deflections for the all titanium case were calculated, a comparable composite part was designed. Polymer matrix composites were chosen for their high stiffness to weight ratios and for their easier processing and lower cost as compared to metal matrix components. IM7 fibers with YLA Inc.'s RS-47 resin were selected for use in the hoop (90º) direction and M55J fibers with YLA's RS-33 resin were chosen for the axial (0º) direction. Both resins are toughened epoxies with 177º C (350º F) cure cycles. These two material systems were chosen primarily because they were readily available to fabricate the part. A monocoque shell design was selected for ease of manufacturing.

The Abaqus FEA model was modified for the composite shell by replacing the solid titanium part with a thin shell. The elements were changed from tetrahedrons (C3D4) to a mix of triangular and tetrahedral shell elements (S3 and S4). Candidate lay-ups were designed outside of Abaqus using PC-Laminate and their smeared properties were entered into Abaqus as lamina materials with the shell thickness set to the laminate thickness. A number of different candidate lay-ups could be easily and quickly evaluated this way.

For the most promising candidates, the Abaqus model was changed such that the laminates were built ply by ply. This produced a more accurate model and allowed for the examination of ply by ply stresses. The final laminate chosen was $(90_2/0_5/90_2/0_5/90)_s$. The model predicted a vertical muzzle deflections of 12 mm under a 1 g load compared to 11 mm for the titanium part and 70 mm under a 6 g load compared to 64 mm. Additionally the tube support was predicted to increase the stiffness of the gun system by increasing the first mode from 7.10 to 7.57 Hz and the second mode from 32.81 to 35.41 Hz as compared to the gun without a support. The shell thickness for the composite was designed to be 3.81 mm compared to 15 mm for the titanium design, resulting in a predicted weight savings of almost 70% over the 95.25 kg (210 lb) titanium design. Given the thinness of the shell, the FEA results were checked for any signs of buckling but none were found. Figure 4 and

Figure 5. Stresses in the composite shell under a 6 g loading using ply-by-ply properties

Figure 6. Filament winding the primary support shell

Figure 5 show plots from Abaqus of the stresses in the tube support under a 6 g loading using smeared and ply-by-ply properties, respectively.

Besides designing the composite shell itself, a method of joining the shell to the two titanium end frames had to be selected. An adhesive joint was deemed preferable to a bolted or riveted construction primarily for ease of assembly. After determining the maximum shear load that the joint was likely to see, Loctite Hysol EA9392 two-part paste adhesive was selected.

3. MANUFACTURE

Two tube supports were needed; one as the primary and a backup in case the first one was damaged during firing. The primary support was made completely in house at Benét Laboratories utilizing a two-axis filament winder. The shell for the backup support was contracted out and made on a fiber placement machine. An aluminum mandrel with 5 mm radii on all edges was used for both shells.

For the primary shell, the hoop fibers were filament wound while the axial fibers were applied by hand from pre cut sheets of 304.8 mm (12") wide pre impregnated tape. Half way through the lay-up process the part was placed in a vacuum bag and allowed to debulk for 1 hour. After the lay-up was completed, the part was vacuum bagged and cured in an autoclave. The cure cycle was for two hours at 177º C (350º F) with the temperature based on the lagging thermocouple and a low temperature vacuum hold. Figure 6 shows the primary support on the filament winder.

The backup shell was manufactured using basically the same process with the major difference being that the hoop fibers were applied using a tape placement machine. The axial fibers were still applied by hand. Additionally, the second support was wrapped in shrink tape before vacuum bagging whereas the first shell was not. Overall the second shell appeared to be better consolidated and showed fewer surface wrinkles. One possible problem with the second support was that the laminate was only half as thick around the corners as the first shell.

After the supports were cured, they were rough cut to length and then fitted to the titanium end frames. Due to spring back from the curing process, the shell was not exactly sized to fit the end frames. To ensure a proper fit, the end frames were machined down to generate a 0.127 mm gap between the shell and the end frames. The end frames were vapor degreased and chemically etched according to the Loctite Hysol Surface Preparation Guide. Loctite Hysol EA9392 was then used to bond the shell and end frames together. An alignment jig was used during this process to ensure that the centers of the end frames remained concentric and that the end surfaces were parallel.


Figure 7. Finished Tube Support

The final assembly step was to apply the strain gauges. Due to time constraints, only the primary support was instrumented. Six Micro Measurements model CEA-06-250UR-120 tri-directional strain gauge rosettes were applied with the three directions aligned to 0º/90º/45º with 0º being axial. The gauge locations are detailed in Table 1 and shown in Figure 8. After application of the strain gauges, a thin layer of epoxy was applied to the inside of the shell as the inside surface appeared to be rather dry. This layer of epoxy not only helped protect the fibers, but the internal gauge and its wiring as well. The final assembled tube support can be seen in Figure 7.

Table 1. Strain Gauge Location

Gauge Location #	Location
1	~930mm from rear of support on top, just after octagon starts, near right edge of top flat
2	930mm from rear of support on 45 degree flat, just before octagon starts, centered on flat
3	On the inside directly opposite gauge 2
4	~32mm from rear of support on top, ~15mm in from the edge, just forward of Ti end frame
5	~530mm from rear of support on the right side, centered
6	Mirror of gauge 1, so on bottom flat but left edge
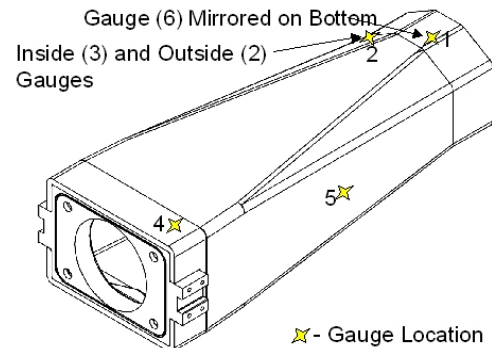
Figure 8. Strain Gauge Locations

4. NON-DESTRUCTIVE EVALUATION

A series of tests, to include a load test, acoustic emission and ultrasonic inspection, were conducted to assess the condition of and validate the FEA model of the tube support. The tests were conducted before firing to ensure the tube support was safe for firing. After firing, an inspection was done to assess whether or not damage was caused by the firings.

The first test to be conducted was the load test. The primary purpose of this test was to ensure that the strain gauges were working and that their response matched those predicted by the FEA model. First, the launcher assembly was mounted on a hardstand (Figure 9), the tube was leveled, and the strain gauges were zeroed. Next, the tube was released and the strains and vertical muzzle deflection due to a gravity load were recorded. Weights were then suspended from the muzzle in 22.7 kg (50 lb) increments up to 113.4 kg (250 lb) and strain and deflection readings were taken. Finally, the tube was then unloaded in the same order and the values were recorded. This load and unload sequence was repeated twice.
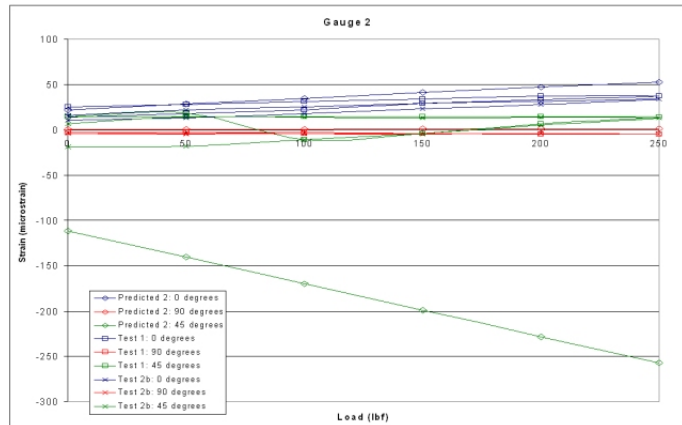

Figure 9. Load Test Setup

These values were then compared to the results of the FEA model of the loading. The deflections were close, with both the model and the experiment showing 28.5 mm at the 90.7 kg (200 lb) load. The strain values were not as close, but the trends were the same. The parameters of the FEA
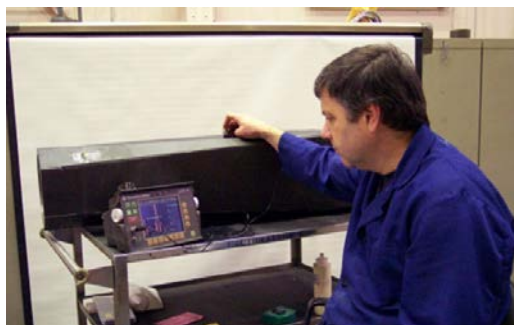
model were then adjusted to improve the match with the experimental data. Figure 10 shows a plot of the expected vs. measured values for strain gauge 2. It can be seen that for the 0° and 90° gauges there is good agreement between the model and experiment. The 45° gauges could never be matched satisfactorily.

An acoustic emission test of the structure was performed at the same time as the load test. A Physical Acoustics 8 channel DiSP system was used with their R151

Figure 10. Experimental vs. FEA Strains for Gauge 2

sensors. Four sensors were placed at both the front and back of the support, coupled to the structure with vacuum grease and secured with duct tape. Two of the front sensors are visible in Figure 9. A few hits were detected during the process but nothing of significance was found.

After the firing, the tube support was removed from the launcher and visually and ultrasonically inspected (Figure 11). No obvious damage was visually detected and the interior layer of epoxy showed no evidence of cracking or crazing. A Krautkramer USN-60 Ultrasonic Flaw Detector with a 0.9525 cm (0.375") diameter, 2.25 MHz Zip probe was then used to inspect for internal damage. No damage was detected within the laminate. However, several large voids were

Figure 11. Ultrasonic Inspection of the Support

detected at the interface between the composite and the titanium end frames.

Since the ultrasonic inspection had not been performed prior to firing, it was not readily apparent as to whether these voids were caused by manufacturing or firing. The backup support was never fired, so it was inspected to determine the likely pre-firing state of the support. The backup support also exhibited void areas in the joints between the end frames and shell, though they were smaller than in the primary support. It was deemed that the voids were most likely caused by the manufacture process and not firing.

5. TEST FIRING

In July 2003 the FCS-MRAAS Swing Chamber Launcher was test fired at the Aberdeen Proving Grounds. The cannon was fired in both direct (0° elevation) and indirect (30° elevation) fire modes with a mix of kinetic energy simulator and cargo type rounds. In total, 11 rounds were fired at pressures ranging from 138 MPa (20 ksi) to 552 MPa (80 ksi). Table 2 shows the pressure and elevation for each round fired. Figure 12 shows the cannon firing in both the direct (left) and indirect (right) modes. In the indirect picture, the round can actually be seen in the upper left corner. The pepper pot muzzle brake used causes the large cone of flame seen radiating from the muzzle.

Table 2. Rounds Fired

Round #	Pressure MPa	Elevation deg	Round #	Pressure MPa	Elevation deg
1	138	0	7	483	0
2	138	0	8	483	0
3	207	30	9	207	30
4	138	30	10	552	0
5	414	0	11	552	0
6	414	0			

All of the axial and hoop strain gauges detailed in Table 1 were used. However, only the 45 gauge at locations 1, 5, and 6 were used due to channel count restrictions. Data was taken at a sample rate of 200 kHz for 1126.39497 ms after triggering. A pretrigger of 51.2 ms was used to give a total of 235520 data points per channel per shot. The trigger was the sending of the firing signal to the cannon. After the first shot, the axial gauge at location #2 ceased to function properly. Losing a gauge is not unusual firing a test firing and in fact almost half the strain gauges on the gun tube failed over the course of the firing test.

Additionally, three Endevco model 7270A-20 accelerometers were mounted on the left side of the support at the front. The accelerometers were attached to a mounting block that was screwed through the shell into the titanium end frame and aligned so as to capture axial (X), vertical (Y), and horizontal (Z) accelerations. The accelerometers were sampled at the same rate and with the same pretrigger. However, only 460.79499 ms of data was taken, so there are only 102400 samples per channel.

Figure 12. FCS-MRAAS Swing Chamber Launcher Direct (left) and Indirect (right) Firing

After firing, all data was smoothed and interference was removed using Matlab. The following figures present the axial data for five of the six gauge locations with one trace for each pressure.
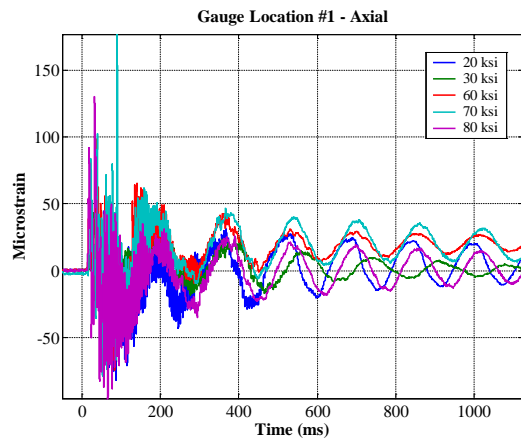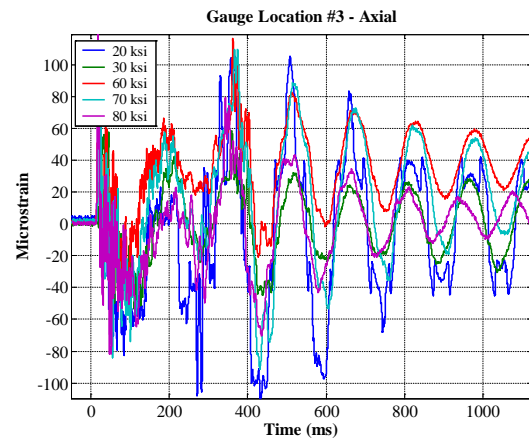

Figure 13. Axial Strains at Gauge Location #1

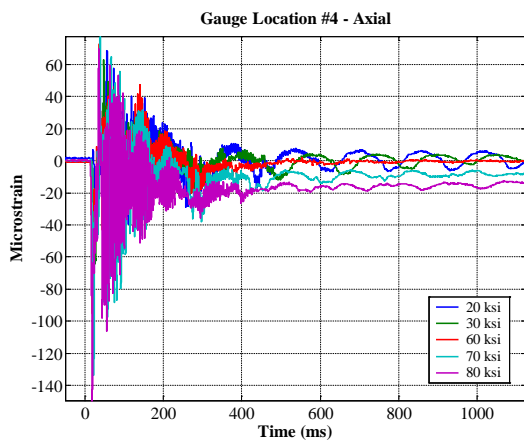**Figure 14. Axial Strains at Gauge Location #3**
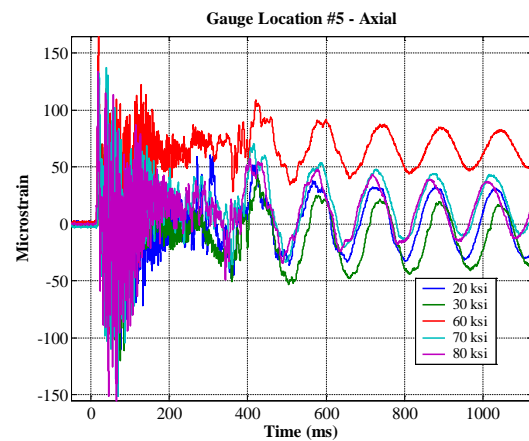

Figure 15. Axial Strains at Gauge Location #4
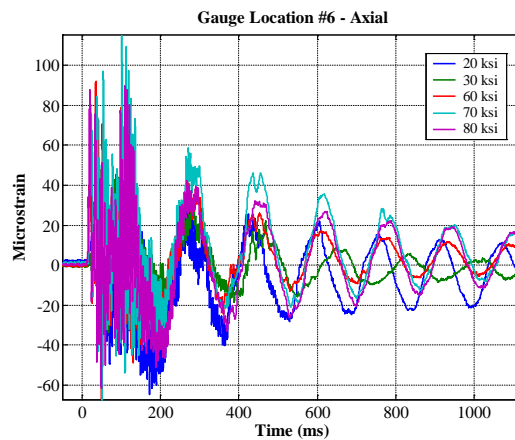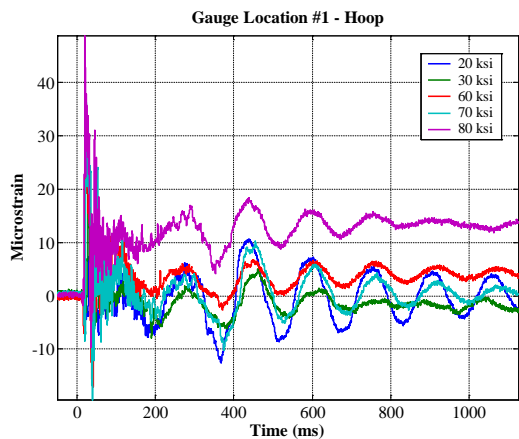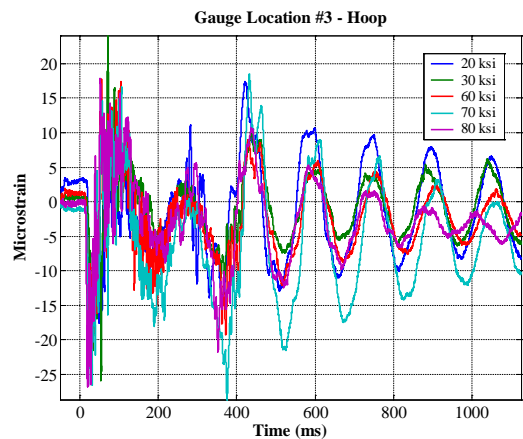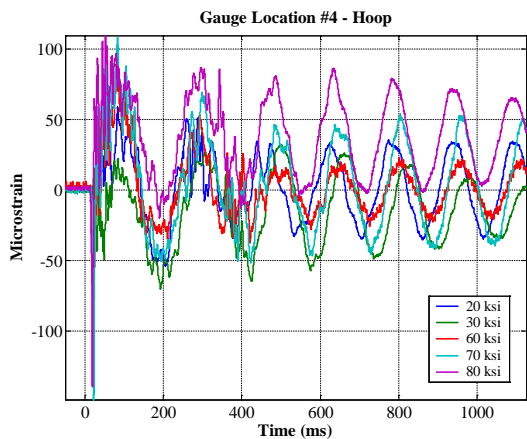

Figure 16. Axial Strains at Gauge Location #5

Figure 17. Axial Strains at Gauge Location #6

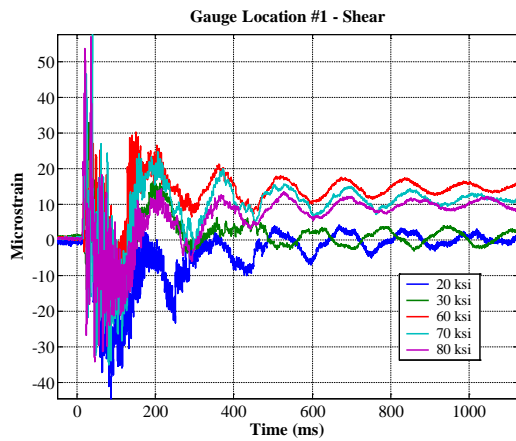The following figures present the hoop data for five of the six gauge locations with one trace for each pressure.
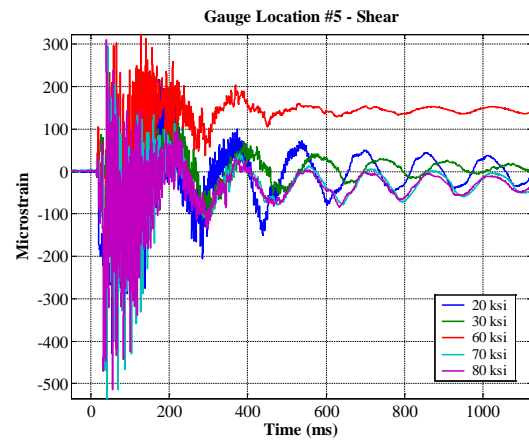

Figure 18. Hoop Strains at Gauge Location #1

Figure19. Hoop Strains at Gauge Location #3

Figure 20. Hoop Strains at Gauge Location #4
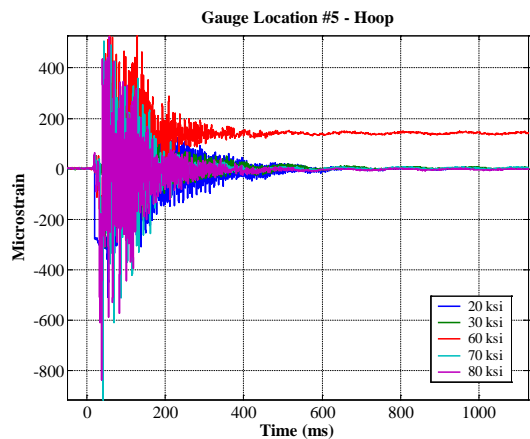
Figure 21. Hoop Strains at Gauge Location #5
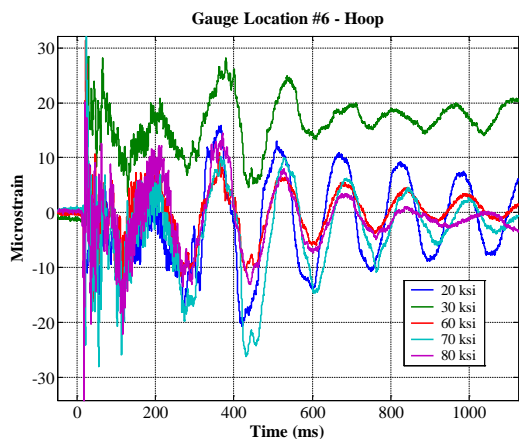
Figure 22. Hoop Strains at Gauge Location #6

The following figures present the shear data for three of the six gauge locations with one trace for each pressure.

Figure 23. Shear Strains at Gauge Location #1

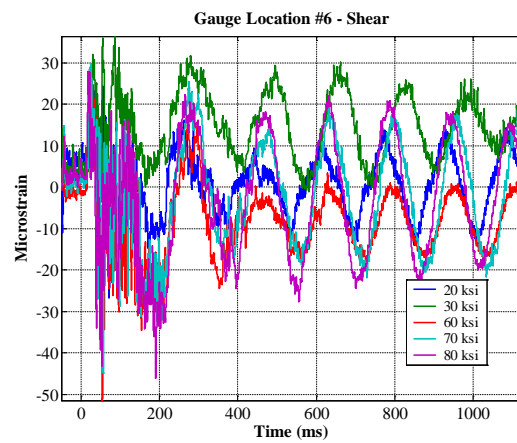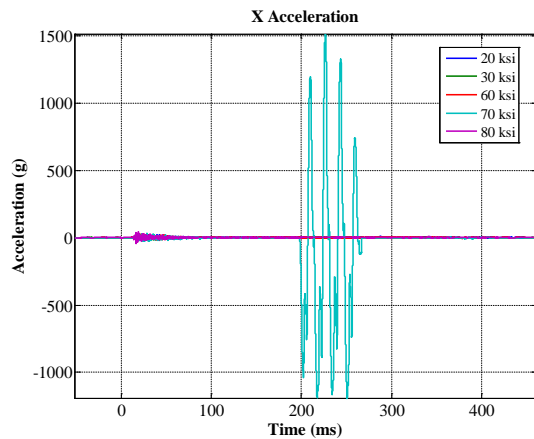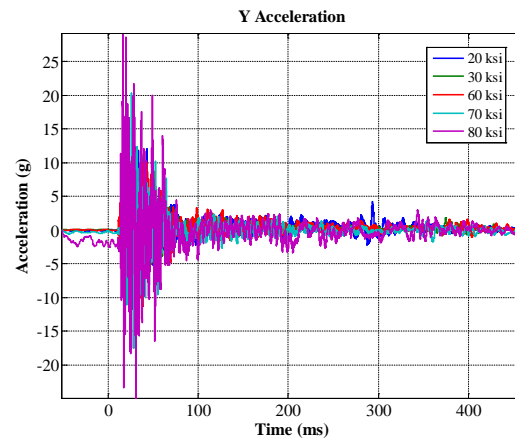Figure 24. Shear Strains at Gauge Location #5
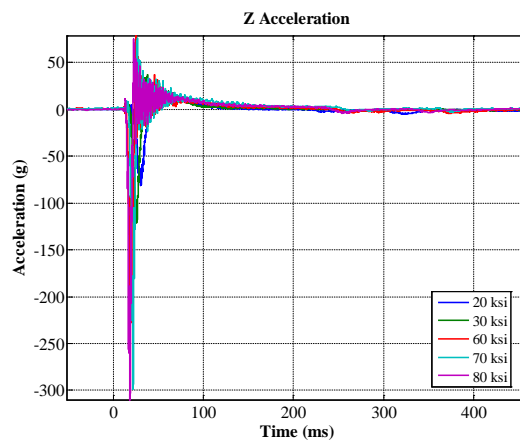

Figure 25. Shear Strains at Gauge Location #4

The following figures present the acceleration data for the x-, y-, and z-directions with one trace for each pressure.

Figure 26. Acceleration data in the X-direction

Figure 27. Acceleration data in the Y-direction

Figure 28. Acceleration data in the Z-direction

The responses were largely as expected with overall strain levels being around 150 microstrain. The responses for gauges 1 and 6 mirrored each other as they should. Also, the frequency of the ringing was found to coincide with the natural frequency of the support at 7.5 Hz. Initially, the response for the low-pressure shots was higher than expected, but this was later found to be due to the interaction between the projectile and the gun tube. Two still unexplained items though were the high level of damping during the high-pressure shots and the large horizontal and vertical accelerations. A high, though not this high, vertical acceleration is normal but the horizontal acceleration is not normally at the same level.

The Abaqus FEA model that had previously been used to model the non-destructive testing was also used to model the test firing at a pressure of 552 MPa (80 ksi). The model determined strains throughout the tube support for the first 8 milliseconds after firing. This time was much shorter than the real firing because of the lengthy computational time of the complex FEA model. The data from each of the strain gauges was compared to data from its corresponding element in the FEA model. This comparison produced mixed results. The basic trends for most
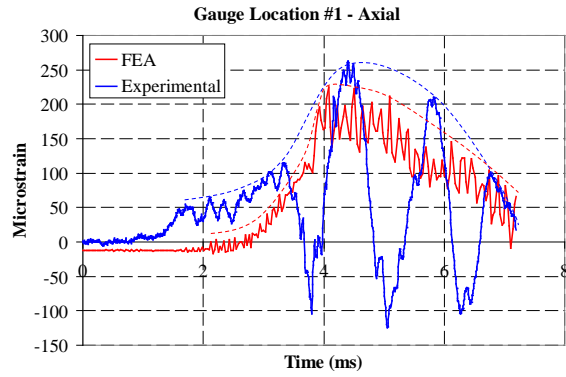
Figure 29. FEA Axial Strain at Gauge Location #1
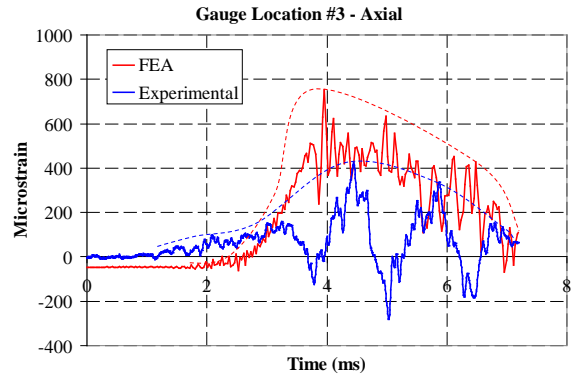
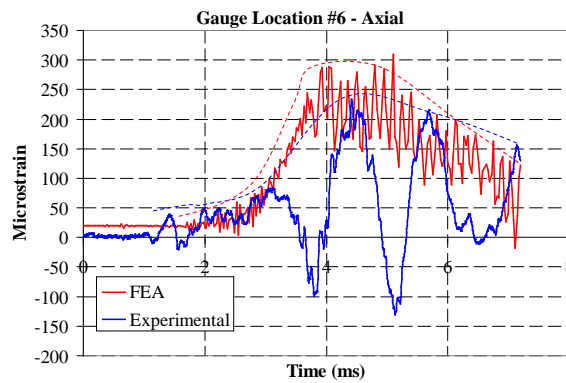
Figure 30. FEA Axial Strain at Gauge Location #3

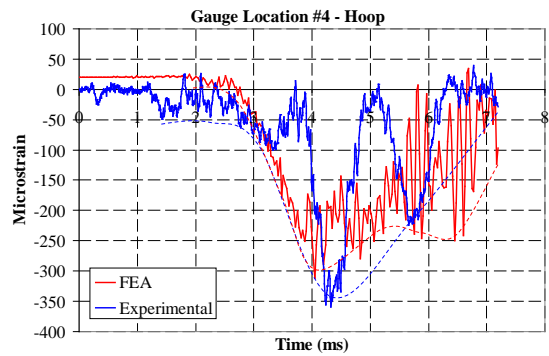Figure 31. FEA Axial Strains at Gauge Location #6

Figure 32. FEA Hoop Strains at Gauge Location #4
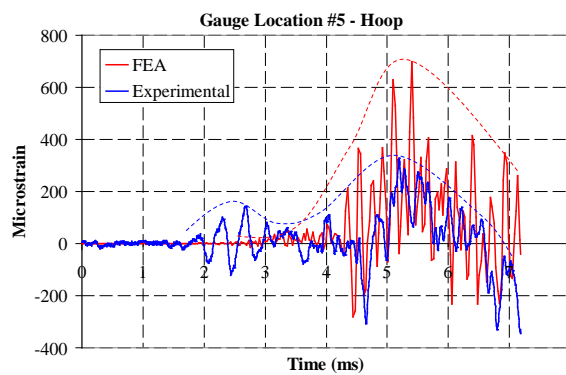

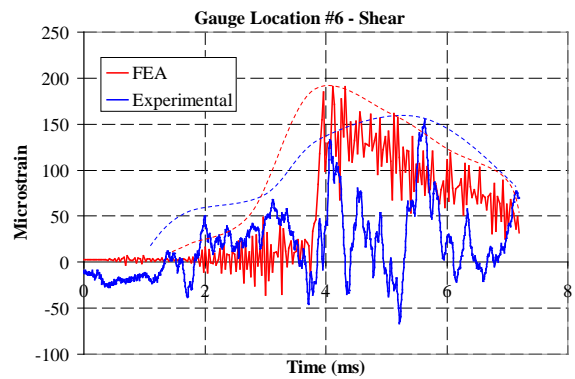Figure 33. FEA Hoop Strains at Gauge Location #5

Figure 34. FEA Shear Strains at Gauge Location #5

of the gauges were accurate, but the experimental data had an extra frequency, at 700 Hz, present that made the data appear inaccurate. The data matches in the trends of the maxima of the strain waves. The extra frequencies that are present, as well as any other differences, are more likely due to one of two things. First, the FEA model was more rigid than the real life assembly. Tie constraints were used to model the interactions between parts, whereas there was sliding and the compliance of the bonded joints in the real test article. Second, the strain gauges were bonded to hoop fibers, which support load mainly in one direction rather than in all directions like a typical metal. This means that certain stresses could have in actuality been representing strain inaccurately in certain directions. Despite these issues, the FEA model and firing data were suitable matches. Figure 29 through Figure 34 show some of these comparisons. The dashed lines above the peaks show how the extrema match correctly. It can be easily seen where the extra frequencies affect the data.

6. CONCLUSION

A composite tube support was designed to increase the stiffness of the gun tube and provide a longer wheelbase for improved accuracy, while minimizing weight. The composite support was designed to have the same deflections as an all titanium design but weigh 70% less. It was successfully manufactured, non-destructively evaluated and then test fired. Though there were a few surprises in the firing data and the match to FEA results were not as good as could be hoped for, in general the results were as expected. In all the composite tube support can be declared a success and its firing performance regarded as superb.

7. BIOGRAPHIES

Dr. Andrew Littlefield, a senior research engineer at Benét Laboratories, holds a Ph.D. in Mechanical Engineering from Rensselaer Polytechnic Institute. Prior to joining Benét in 2000, Dr. Littlefield worked for the Air Force Research Lab on applying composites to spacecraft structures on several programs. Dr. Littlefield is the lead composite engineer at Benét and has worked on composite gun tubes, a composite gun tube support for FCS-MRAAS, and gun barrel vibration absorbers. He has been the lead author on journal papers, several conference papers, and technical reports. He is a member of ASME, Tau Beta Pi, and Pi Tau Sigma.

Joshua Root graduated from Cedarville University in May 2004 with a degree in Mechanical Engineering. While at Cedarville, he served as president of the university's ASME chapter and its Tau Beta Pi chapter. He started at Benét Laboratories in June 2002 as a student trainee and worked on various projects performing FEA analyses, researching composite materials, and studying high speed photography. Joshua started full time at Benét after his graduation and now holds the position of mechanical engineer.

Martin Leach graduated with an AS/ES from HVCC, BS/ME from Union College, & took several courses at RPI. He was hired at Watervliet Arsenal in 1984 where he specialized in FEA. Martin has worked in various projects from E/M gun analyses, bunker buster impact studies, & numerous gun dynamic programs.